

The Virtual Wave Observatory (VWO): A Portal to Heliophysics Wave Data



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Abstract

The Virtual Wave Observatory (VWO) is one of the discipline-oriented virtual observatories that help form the nascent NASA Heliophysics Data environment to support heliophysics research. It focuses on supporting the searching and accessing of distributed heliophysics wave data and information that are available online. Since the occurrence of a natural wave phenomenon often depends on the underlying geophysical – i.e., context – conditions under which the waves are generated and propagate, and the observed wave characteristics can also depend on the location of observation, VWO will implement wave-data search-by-context conditions and location, in addition to searching by time and observing platforms (both space-based and ground-based). This paper describes the VWO goals, the basic design objectives, and the key VWO functionality to be expected. Members of the heliophysics community are invited to participate in VWO development in order to ensure its usefulness and success.

1. Introduction

The Virtual Wave Observatory (VWO) is the latest heliophysics virtual observatory selected by NASA to help form the Heliophysics Data Environment (HPDE [1]). The primary audience of VWO is the heliophysics wave research community, the main scientific interests of which are in wave phenomena, such as wave excitation, reception, and propagation; wave-particle interactions; and nonlinear wave phenomena. URSI is thus a major constituent of this community. This article introduces and describes VWO, and invites the wave research community to take part in and contribute to VWO development, thus ensuring the usefulness and success of VWO in supporting research into the exciting science involving the wide variety of heliophysics wave phenomena.

Wave phenomena are ubiquitous throughout the heliosphere (Figure 1). The primary objective of VWO is to provide basic wave data and information services to

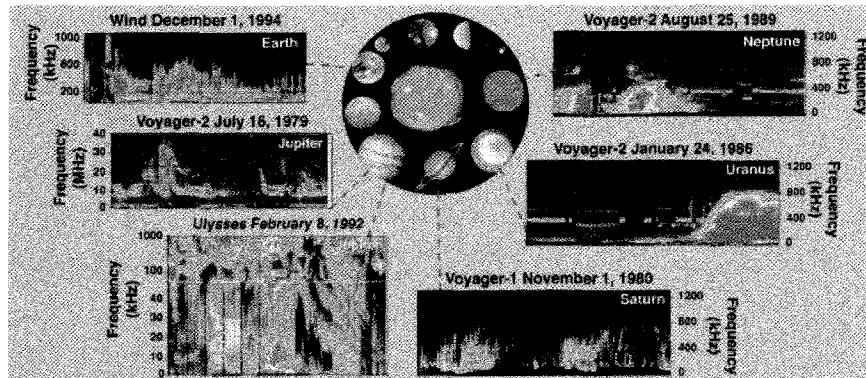


Figure 1. The Virtual Wave Observatory will enable cross-comparison of wave phenomena throughout the heliosphere.

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facilitate wave research in all heliophysics domains: the sun, heliosphere, magnetosphere, ionosphere, atmosphere, and planetary magnetospheres. Like other heliophysics domain-oriented virtual observatories (VxOs), VWO will (1) work with the SPASE [Space Physics Archive Search and Extract] Consortium to develop the SPASE data model and provide wave data terms to the SPASE data dictionary; (2) describe the metadata of heliophysics (space-based and ground-based) wave data sets using SPASE; (3) develop a heliophysics wave data registry; and (4) develop a Web interface for searching, sub-setting, and retrieving distributed wave data. VWO differs from other domain-oriented VxOs in that the defining theme for VWO is the common interest in heliophysics wave phenomena, irrespective of domains. VWO thus aims to promote and facilitate interdisciplinary research that can lead to new and deeper understanding of wave processes and their relations to the structures and dynamics of various heliophysics domains. To that end, the VWO goal is to make all online-accessible heliophysics wave data searchable, understandable, and usable by the heliophysics community.

In the following sections, we describe the challenges confronting researchers (particularly non-wave experts and students) in finding the relevant wave data to support their research. We discuss how VWO might facilitate data search and promote the use of wave data in heliophysics studies.

1.1 Why Develop the VWO?

Heliophysics plasma wave and radiation data are currently not easily computer-searchable, making the identification of pertinent wave data features for analyses and cross comparisons difficult and laborious. Since wave studies span the spectrum of microphysics (kinetic scales) to macrophysics (MHD scales or larger), researchers and students with varied training or expertise may not feel at ease at using wave data. In order to resolve these difficulties, and to allow wave data to contribute more fully to heliophysics research, we are creating VWO to make all online-accessible

heliophysics wave data searchable, understandable, and usable by the heliophysics community.

1.1.1 Unique Characteristics of Wave Data

Wave phenomena, ranging from freely propagating electromagnetic radiation (e.g., solar radio bursts, AKR) to plasma-wave modes trapped in various plasma regimes (e.g., whistlers, Langmuir, and ULF waves) and atmospheric gravity waves, are ubiquitous in the heliosphere. Because waves can propagate, wave data obtained at a given observing location may belong to wave oscillations generated locally or from afar. Each panel in Figure 1 was obtained from a passive wave receiver. The individual frequency-time records are called dynamic spectrograms. A dynamic spectrogram recorded in the Earth's magnetosphere, with many emissions identified, is presented in Figure 2.

Since most wave data are recorded in the spectral domain (e.g., frequency) as well as in the time domain, and because wave data taken at a location (and time) can either be generated locally or from a remote source, searching wave data by time or location alone, as is traditionally the case for in situ particle and field data, is thus not always meaningful. As shown in Figure 2, RPI [the radio plasma imager] aboard the IMAGE satellite detected different electromagnetic emissions in the frequency range of 50-500 kHz at different times (different orbital locations), such as the Earth's intense auroral kilometric radiation (AKR), kilometric continuum (KC) radiation, and solar Type III radio bursts. At lower frequencies, RPI detected in situ electrostatic plasma waves below the local electron gyrofrequency during its passage within the Earth's plasmasphere. A wave dynamic spectrogram can contain a wealth of different plasma and electromagnetic wave phenomena, covering a large spatial volume that may include vastly different heliophysics domains. Hence, tools developed primarily for time-series particle and field data do not work well in serving the needs for searching wave data.

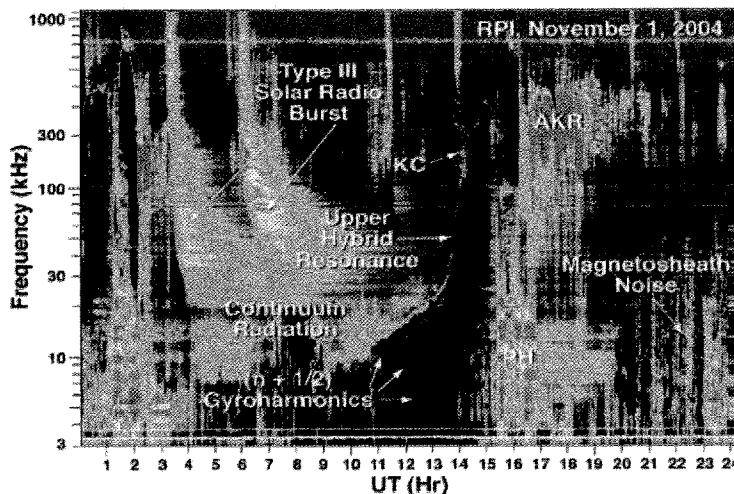


Figure 2. Wave data are often displayed in a dynamic spectrogram. This IMAGE/RPI example shows different electromagnetic free-space mode wave components: type III solar radio burst, auroral kilometric radiation (AKR), kilometric continuum (KC), and non-thermal continuum radiation; as well as a number of localized plasma wave components: plasmaspheric hiss (PH), $(n + 1/2)$ gyroharmonic and upper hybrid resonances, and magnetosheath noise, observed inside and outside the Earth's magnetosphere.

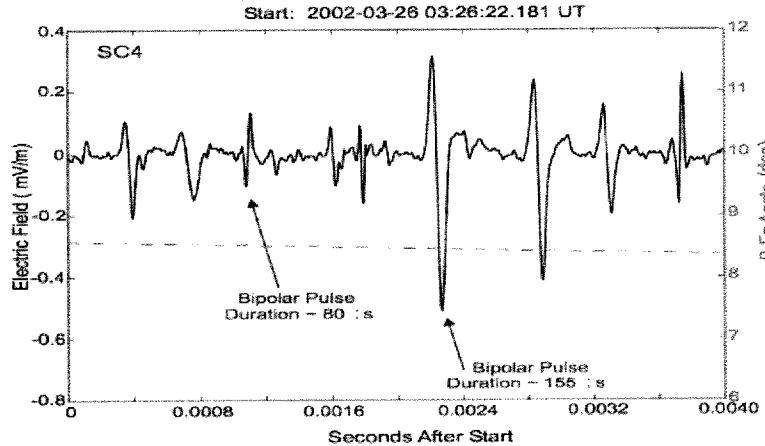


Figure 3a. An example of a high-time-resolution 4 ms sample of waveforms by Cluster Spacecraft 4, showing the isolated, short duration bipolar pulses in broadband electrostatic noise (BEN) observed during bow shock crossings and well into the magnetosheath [5].

In order to serve wave research effectively, we need to devise and implement data-search mechanisms that cater to searching and obtaining pertinent wave and ancillary data sets.

As shown by the example in Figure 2, wave data cannot be selected by frequency alone, in the same way particle data are selected by energy. Data tools for particle and field data must be suitably modified in order to be applicable to wave data. Because of the context-dependent nature of wave observations, it is desirable to be able to select wave data based on geophysical conditions (solar wind, IMF, geomagnetic activity, etc.) and wave phenomena.

In addition to dynamic spectrogram data (e.g., Figure 2), Figure 3 illustrates other wave data types in the forms of time series (A) and a wave map (B). Active sounding measurements can also yield multidimensional wave data on plasmas resonances and echo signals in different wave modes (e.g., [2-4]). Figure 3c presents an example of a plasmagram resulting from radio sounding in the Earth's

magnetosphere. Figure 3 thus illustrates the cross-domain nature and the unique multidimensional characteristics of wave data (frequency, time, location, multi-component intensities, etc.). The diverse wave data types suggest the need for a cross-disciplinary virtual wave observatory to support wave research, and the heliophysics research community in general. The emerging VWO will require close collaboration with all existing and future heliophysics virtual observatories.

A unique aspect of active wave data (e.g., Figure 3c) is that of its complex, discipline-specific metadata. For example, active radio sounding IMAGE/RPI data have extensive metadata associated with each sounding measurement regarding radiated power, frequency range, frequency step size, time per measurement, minimum and maximum virtual range, range increments, pulse repetition rate, pulse width, receiver bandwidth, receiver sensitivity, coherent integration time, Doppler resolution, receiver saturation recovery, Doppler range, amplitude resolution,

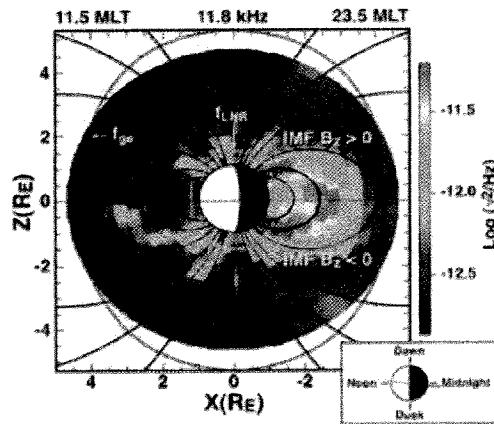


Figure 3b. An example of a wave map of the spatial distribution of wave electric field intensity at 11.8 kHz taken from DE1 observations near the noon-midnight meridian plane [6].

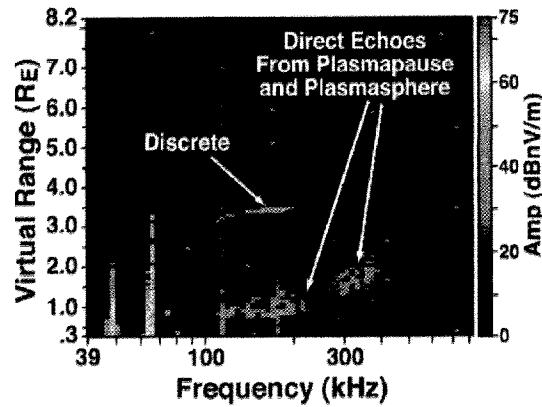


Figure 3c. An example of active radio sounding data from IMAGE /RPI showing plasma resonance (e.g., vertical traces at lower left), discrete guided echoes, and diffuse direct plasmapause echoes [2].

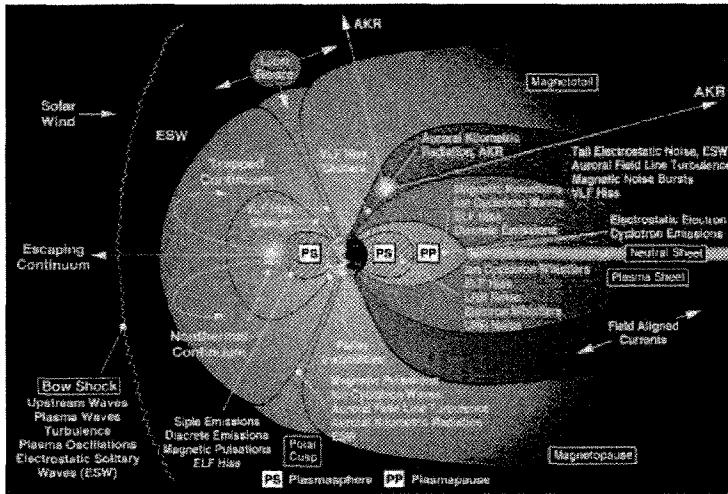


Figure 4. The VWO will provide researchers with sophisticated query tools tailored to this complex environment to better enable science discovery, as illustrated by the abundance of distinct wave phenomena observed in the Earth's magnetosphere (adapted from [8])

angle-of-arrival resolution, antenna length, and processing gain [7]. This uniqueness, and the lack of a metadata standard description within the wave community, warrants a separate focal point to develop SPASE descriptions (Section 1.3) for active and passive wave data.

1.1.2 Wave Research and Heliophysics Science

Heliophysics wave data span most heliophysics domains: solarwind, interplanetary space, Earth's ionosphere and magnetosphere, and planetary magnetospheres. They are thus of multidisciplinary interest. Figure 1 shows observations of radio emissions from different planetary magnetospheres. Cross comparisons of these datasets will help determine, for example, which radio emissions have common emission mechanisms. Wave-propagation studies are also important for elucidating plasma structures in various planetary magnetospheres.

Wave data analysis often requires specialized knowledge of different wave phenomena (e.g., see Figure 4) and the associated physics, such as the propagation characteristics of different wave modes. This specialized expertise requirement can be a hindrance to wider use of heliophysics wave data by non-wave researchers and students, despite the important information wave data can contribute to understanding many heliophysical processes. In addition to the basic data and information services, the VWO will endeavor to enhance the understandability and usability of heliophysics wave data by developing data annotation and tutorial services for describing the data content and illustrating how wave data can be used. Data annotations by expert users will be collected and organized into a searchable database, so that wave data can eventually be organized and searched for specific features and used for comparisons with other heliophysics data sets.

Search for appropriate data for heliophysics wave studies also requires knowledge of wave phenomena. In addition to deciding whether the wave activity of interest is electrostatic (i.e., locally trapped) or electromagnetic (with propagation over distances), considerations must be given to the dependence of the wave activity on the observer's location or viewing geometry, propagating frequency range, and whether the wave data were acquired by passive or active observations. Occurrences of natural wave emissions in the magnetosphere (e.g., auroral kilometric radiation) are often also dependent on the state (i.e., context) of the magnetosphere, which varies with the changing solar wind, IMF, and geomagnetic conditions. Fung and Shao [9] showed recently that magnetospheric state can be specified by a set of suitably time-shifted solar wind, IMF, and the multi-scale geomagnetic response parameters. These parameters form a magnetospheric state vector that provides the basis for searching magnetospheric wave data by their context conditions. Innovative context and content data search capabilities will make VWO a very useful tool for heliophysics research.

1.2 New NASA Heliophysics Data Environment

As described in the recently released NASA Heliophysics Science Data Management Policy [10], the Heliophysics Data and Model Consortium (HDMC) is a project established by NASA to provide *open, easy, uniform, and scientifically meaningful* access to its heliophysics mission data and models. The HDMC oversees all heliophysics mission-resident archives, data recovery and upgrade projects, and discipline (x)-oriented Virtual Observatories (VxOs). It leads the SPASE consortium [11] in developing the heliophysics data model used for describing heliophysics metadata.

VWO [12] is one of the latest VxOs selected to complement the overall heliophysics data environment. In addition to VWO, the current suite of VxOs includes:

- Virtual Solar Observatory (VSO, [13])
- Virtual Heliospheric Observatory (VHO, [14])
- Virtual Energetic Particle Observatory (VEPO, [15])
- Virtual Magnetospheric Observatory (VMO, [16])
- Virtual Radiation Belt Observatory (VIRBO, [17])
- Virtual Ionosphere, Thermosphere and Mesosphere Observatory (VITMO, [18])
- Virtual Modeling Repository (VMR, [19])

As suggested by their names, each of the VxOs is identified by its respective domain or associated domain science, and is expected to (1) serve its respective discipline community and the heliophysics community as a whole; and (2) enable effective use of discipline data sets (e.g., to enhance scientific returns of the data), likely in accordance with how the discipline/domain science is practiced.

1.3 SPASE

In order to support wave research across different heliophysics domains, there needs to be ready availability and accessibility of wide varieties of wave and ancillary data, and effective data search and retrieval mechanisms to handle the selection and retrieval of diverse wave-data products, as illustrated in Figures 2 and 3. The wave-research community already has made available heterogeneous (instrument-specific) metadata and data for many of its publicly available, distributed datasets (e.g., in NASA's CDAWeb [20] and Planetary Data System [21]). However, there exists no metadata standards to enable effective searches across distributed archives and inter-comparisons of the data. Although wave data providers have made great strides in documenting their data sets and storing many of them online or near-online in self-describing data formats (e.g., the NASA Common Data Format, CDF), the lack of metadata standards hinders our ability to effectively draw together diverse data sets, including those from particle and field instruments, for analyses.

SPASE, which stands for Space Physics Archive Search and Extract, is now the recognized standard data model adopted by the VxO community to facilitate data searches between members. It is an open activity, involving an international team of solar, heliospheric, and space physicists and information scientists engaged in the process of defining standards for data descriptions and archive interoperability. The SPASE development effort is under the oversight of the SPASE Group Consortium [11], which

is responsible for official release and documentation of the SPASE data model. The VWO has been working with the SPASE Group Consortium to develop SPASE terms for describing active and passive wave data. This effort has contributed to the release of SPASE 2.0. The wave-research community is invited to contribute to this effort so that all wave data can be effectively described.

2. VWO Description

2.1 VWO Goal

The VWO is a data service dedicated to serving the wave-research community having primary scientific interest in wave phenomena and how they relate to processes in the heliosphere. Its aim is to provide access to wave and ancillary data to support wave research. The VWO is thus especially suited to serve the science goals of Commission H of the International Union of Radio Science (URSI) [22]:

(a) to study waves in plasmas in the broadest sense, and in particular in: (i) the generation (i.e., plasma instabilities) and propagation of waves in plasmas, (ii) the interaction between these waves, and wave-particle interactions, (iii) plasma turbulence and chaos, and (iv) spacecraft-plasma interaction, and (b) to encourage the applications of these studies, particularly to solar/planetary plasma interactions, space weather, and the exploitation of space as a research laboratory.

Also of interest are nonlinear wave phenomena, such as solitary waves, ponderomotive forces, and nonlinear wave-particle interactions. To accomplish its goal, the VWO endeavors to make all online-accessible heliophysics wave data searchable, understandable, and usable.

2.2 VWO Design Objectives

The development of VWO as a data service is guided by the desire for VWO to offer *ease of use* and *efficacy* in satisfying users' requests. To that end, the VWO will strive to:

- (1) Have a simple but functional user interface;
- (2) Provide data search options (in addition searching data by time, spectral range, and observing platform) to satisfy needs for data in different contexts, such as spatial location, solar, solar-wind and magnetospheric conditions, etc.
- (3) Be interoperable with other VxOs and data services in order to locate and provide access to all online heliophysics discipline data and information;
- (4) Provide tutorial and educational materials to explain heliophysics wave data and to illustrate how they may

be utilized more broadly in heliophysics research; and

(5) Develop a wave-data annotation service with which data-feature annotation by expert users can be captured and organized into a searchable database.

2.3 VWO Architecture

Like most VxOs, the VWO functions as “middleware” between users and distributed data sources. It accepts users’ input queries, and then locates (and delivers when feasible) data granules and information available from appropriate data sources to support heliophysics research. Successful VWO operations require seamless handshake for information exchange between different components: end users, middleware, and data sources. The schematic in Figure 5 shows the relationships between VWO middleware and other HDMC components.

In order to limit development cost and minimize duplication of effort, the VWO middleware will be based largely on the existing VHO and VMO architecture. However, the existing virtual observatories are geared toward providing primarily time-ordered data, because time is traditionally the key organizing parameter for most space-physics data. In addition, the VHO and VMO also provide statistical summaries of magnetic-field and plasma data. These tools are not applicable to finding and accessing wave data organized in the spectral domain. The VWO middleware will thus need to provide data-search mechanisms and an interface catered to wave studies.

As shown in Figure 5, central to VWO middleware is the VWO Query Manager (VQM) the primary function of which is to decipher users’ queries and determine appropriate resources that satisfy the queries. Figure 6 shows a more-detailed view of the various query types and services that the VQM will have to manage and be accessed by other services via Web services or application programming interfaces (API).

The middleware will store and have access to context (such as solar wind, IMF, and geomagnetic indices information) and orbit information, and event catalogs from which appropriate time and spatial constraints can be determined. Queries to VWO will result in the appropriate restrictions being determined from user queries. These restrictions will be sent as appropriate to domain virtual observatories (VHO, VMO or VITMO) to query for data availability.

In order to implement this architecture, we have identified five tasks as well as the overarching needs to work with other VxOs and the SPASE community. These detailed tasks and our plan to implement them are discussed in the following subsections.

2.4 VWO User Interface

The VWO aims to serve different user categories: scientists (both wave experts and non-experts), data providers, students, and educators. A research scientist may look for data to perform scientific analysis, a data provider may need information about how to contribute to the VWO

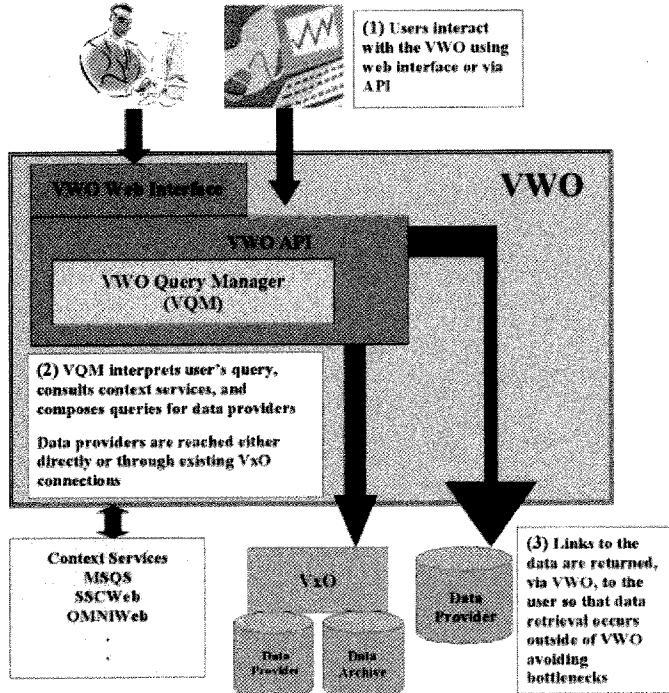


Figure 5. A schematic of the VWO architecture. The VWO middleware (grey shaded box) will contain a complete set of tools to provide both context and content-based searches for the wave research community. In addition to its own data providers, the VWO will leverage existing VxOs and their data providers whenever applicable.

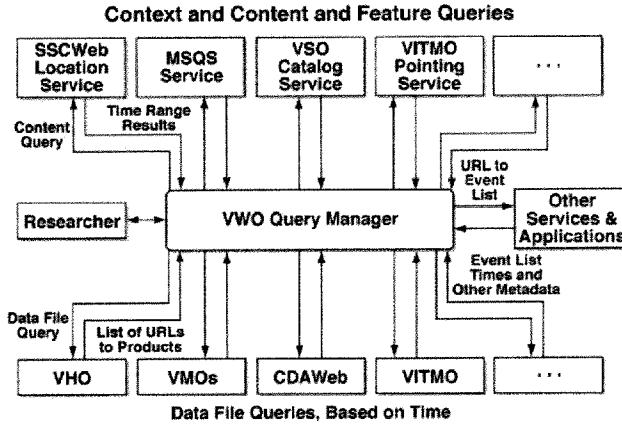


Figure 6. A schematic of VWO's Query Manager system, interacting with various VxOs and distributed data services, to enable content and context queries (top) as well as queries for data files (bottom).

data registry, while an educator or student may need mission information and explanations on wave phenomena and data examples. Since the data needs of different users vary with their interests, background, and expertise, VWO will work toward providing a user-oriented Web interface through which queries posed by different category users can all be effectively answered.

Searching for appropriate data for wave studies can be a daunting task, particularly for non-expert users. A scientist may wish to search for wave data by frequency and observing location, or by wave phenomena, rather than by time and missions, as has been the case traditionally, and may not want data from pre-sorted mission-centric data catalogs. The goal of the VWO user interface is to offer a common yet flexible data-discovery and access tool, i.e., a data-query builder [23], that saves users from having to use many distinct tools and spending an inordinate amount of time to hunt for wave data sources, documentation, and analysis tools. The query builder will be useful for handling complex data queries. Since wave data do not naturally come with identities of wave phenomena, wave data tend to be used less by non-wave experts. VWO will develop tutorial and annotation services to promote understandability and usability of heliophysics wave data.

Since observations of wave phenomena depend largely on observing locations, geophysical conditions, and the pertinent wave modes being observed, it will be convenient to have data-search options based on the contexts in which data are sought. While the VWO interface will allow users to perform traditional search for data by missions and time, it will also support search options according to contextual conditions: magnetospheric state, observing location, measurement types (e.g., active or passive), and wave phenomena.

As indicated in Figure 5, VWO will also develop appropriate APIs suitable for power users who may wish to access VWO services as behind-the-scene users, such as a data provider or a VxO. Since metadata are generally stored in Extensible Markup Language (XML) documents,

the most commonly suited APIs are Web services using, for example, Web Services Description Language (WSDL) [24] or REpresentational State Transfer (REST) [25]. Other API types for call routines in *IDL*, *MATLAB*, or *Java* can also be supported as needed and as resources permit.

2.5 VWO Functions

As stated in the “VO Framework” document [26], “a Virtual Observatory (VO) is a suite of software applications... that allows users to uniformly find, access, and use resources (data, software, document, and image products and services using these) from a collection of distributed product repositories and service providers. A VO is a service that unites services and/or multiple repositories.” To effectively serve various user categories, the VWO will provide five core services: (1) data query, (2) data registry, (3) accessing other data services, (4) annotation and education, and (5) tools.

2.5.1 Data Query

Providing access to heliophysics wave data is a primary VWO function. As such, the VWO seeks to become a major portal to both space-based and ground-based heliophysics wave data sources. As mentioned above, the VWO middleware and interface will provide different data-query options. In addition to supporting traditional data search by time, spectral range, and observing platform, the VWO will implement context data search mechanisms [23] with which *multiple* and *distributed* wave data sets can be searched by:

- Location: this option allows users to specify an observing location, such as a ground station, a local time zone, or a spatial region, at which the desired data were taken;
- Magnetospheric state: this option, applicable particularly to magnetospheric wave phenomena,

allows users to specify the solar activity, solar wind, interplanetary magnetic field, and geomagnetic conditions under which the desired data were taken; and

- Wave phenomena: this option, when implemented eventually (see Section 2.5.4), will be useful for obtaining data pertaining to a given wave phenomenon.

Like most heliophysics studies, investigations of wave phenomena will often require using ancillary data sets, such as solar wind or other *in situ* particle and field measurements. In the current heliophysics data environment (HPDE, Section 1.2) under HDMC oversight, it is envisioned that all data sets registered with VxOs should be accessible from any one VxO (see Section 2.5.3). SPASE (Section 1.3) is being developed to provide the *lingua franca* between VxOs from which all VxO-registered data sets can be queried and accessed without further user intervention.

2.5.2 Data Registry

Registration of a data set with a VxO is the key step by which the data and metadata of the data set become accessible to and searchable by VxOs. Data-set registration means that all relevant metadata pertaining to the data set are described by a set of *XML* documents that conform to the SPASE data model. The responsible VxO then maintains the *XML* documents of all the data sets registered with it in

a database, and makes it searchable by other VxOs. Since the selection of the VWO for development, the VWO team has been working with the SPASE Group Consortium [11] to define wave-data terms to be added to the SPASE data dictionary, which will facilitate registering wave data sets at the VWO. This effort has contributed to the formal release of version 2.0 of the SPASE data model.

Tables 1 and 2 respectively list a number of space-based and ground-based wave data sets relevant to the VWO. The data sets in bold lettering are the data sets being targeted initially for registration with the VWO. In fact, the IMAGE RPI data, consisting of *both* active radio-sounding and passive wave measurements, have been used to aid with defining wave data terms for the SPASE data model. We expect the VWO data registry to grow in time with the inclusion of additional national and international space missions, as well as ground-based data sets.

VWO will work closely with other VxOs (last column in Table 1) and other data providers (e.g., the NASA CDAWeb system [20]) to ensure interoperability, so that users can seamlessly access the data sets registered at those facilities. The VWO will work with current and upcoming missions (e.g., THEMIS, RBSP) in order to have those data served within the Heliophysics Data Environment. As the VWO registry matures, we will reach out to the international space-based and ground-based heliophysics community to register additional heliophysics wave data sets.

Mission (Experiment/Data Types)	Time Span	VxO Cross Reference
Alouette 2 (Sounder/digital ionograms)	1965 – 1975	VITMO
ISIS 1 (Sounder/digital ionograms)	1969 – 1984	VITMO
ISIS 2 (Sounder/digital ionograms)	1971 – 1984	VITMO
Hawkeye (ELF-VLF/spectrogram)	1974 – 1978	
ISEE 1 & 2 (Plasma wave, VLF)	1977 – 1987	
Voyager 1 & 2 (PRA/spectrogram)	1977 – 1989	
Voyager 1 & 2 (PWS/spectrogram)	1978 – 2000	
ISEE 3/ICE (Plasma waves spectrum analyzer)	1978 – 1997	
ISEE3/ICE (Radio Mapping of solar wind disturbances)	1978 – 1997	
DE 1 (PWI/spectrogram)	1981 – 1990	
Galileo (PWS/spectrogram)	1989 – 2003	
CRRES (Plasma wave)	1990 – 1991	
Ulysses (URAP/spectrogram, waveform, direction)	1990 – present	
Geotail (PWI)	1992 – present	
Wind (Waves/spectrogram)	1994 – present	VHO
Polar (PWI/waveform, spectrogram)	1996 – 1997	
Cassini (RPWS/spectrogram)	1997 – present	
IMAGE (RPI/spectrogram, plasmagram)	2000 – 2005	
Cluster (DWP, EFW, STAFF, WHISPER/spectrogram)	2001 – present	
Cluster (WBD/waveform, spectrogram)	2001 – present	
STEREO (SWaves/spectrogram)	2006 – present	VHO
THEMIS (EFI, SCM/waveform, spectrogram)	2007 – present	

Table 1. VWO-relevant space-based data sets.

Ground Observatory (Experiment/Data types)	Time Span	VxO Cross Reference
Augsburg College AGO (Search coil Magnetometer/spectrograms)	1993 – 2008	
U. Maryland AGO (Magnetometer, Riometer & VLF/Survey plots)	1986 – 2005	
Augsburg College Svalbard (Search coil Magnetometer/spectrograms)	2006 – 2008	
NCAR Svalbard (Search coil Magnetometer/daily data files)	2006 – 2008	

Table 2. VWO-relevant ground-based data sets.

2.5.3 Accessing Other Data Services

As a VxO, VWO supports the overall HDMC goal to enable researchers and students to search and access heliophysics wave data *without* having to contact multiple data providers and data centers separately, although it may still be necessary to obtain guidance on the proper use of data from instrument teams. In order to locate and provide access to all heliophysics online data and information resources, VWO will work closely with existing VxOs. It will leverage the tools and middleware being developed by those VxOs in order to economize on development effort and cost, and to avoid duplication of effort. In particular, VWO will rely on close collaboration with Goddard's VMO and VHO. These two VxOs share a common architecture. As such, they allow us to work with two diverse heliophysics sub-disciplines while minimizing technical implementation challenges. In particular, both VHO and VMO plan to offer data searching based on user-contributed event lists. This capability fits naturally with the VWO plan to convert context queries into lists of times suitable for other VxOs.

As mentioned in Section 2.5.1, SPASE is the basis of the *lingua franca* between VxOs. Efforts are now underway to develop *SPASEQL* [27] within the HPDE to use the SPASE data model and associated terminology to create a standardized communication language for HPDE Virtual Observatories. *SPASEQL* defines *XML*-based standards for query and response message construction such that VxOs can have a common language for communication [28]. With *SPASEQL* or a similar language in place, software tools can be rapidly developed and used throughout the HPDE. The VWO will work with our collaborating data providers and VxO partners, the SPASE consortium, and community wave researchers to define the standard SPASE terms to describe wave metadata.

2.5.4 Annotation, Tutorial and Education Services

As illustrated by Figures 1-4, there exist numerous wave phenomena throughout the heliosphere. They appear in different portions of the frequency spectrum, can be electromagnetic or electrostatic, and can have natural or artificial sources. Although wave experts often can identify the wave features in which they are interested relatively

easily, it can sometimes be a challenge for non-wave experts to identify a wave phenomenon from data, because wave measurements do not always come with wave-mode identifications, which are critical for understanding the data. For example, in contrast with particle data, electron/ion measurements at different energies are still electron/ion measurements, even though details of the phase-space distributions in different energy regimes may differ.

To make wave data more understandable and usable by the broader heliophysics community, VWO will endeavor to develop capabilities to search wave data by *context conditions* (Section 2.5.1) and *wave phenomena*. In the latter case, it is required not only that data be described by their appropriate metadata (in SPASE), but also identified by their associated phenomena. To that end, VWO plans to develop an annotation service that will capture the data annotations to be provided by wave experts as they analyze the data. The captured information will then be collected, organized, and stored in the VWO searchable metadata database. We hope that the annotation service will become a useful tool that can also help broaden the VWO user base to non-wave experts.

However, in order to develop a successful annotation service, it is important for domain experts to actively contribute to the annotation database. To ensure quality of the captured information, the annotation-gathering procedure has to be an iterative process. A similar “expert rating service” has already been implemented for expert users to identify, rate the quality of, and describe the data features in the IMAGE/RPI radio-sounding observations [29]. With a simple interface as part of the IMAGE/RPI data visualization and analysis software, users can seamlessly submit annotations (and revisions) to a master database over the Internet as they work with the data from their remote workstations. With some organization of the submitted information, the annotations can be used as additional constraints in data queries. The development of the VWO annotation service will thus be based upon the IMAGE/RPI “expert rating service.”

While the VWO annotation service should provide value-added data-search capability, to perform wave data analysis effectively, users still need to possess basic knowledge of wave phenomena and physics of wave propagation, particularly regarding the specific wave mode of interest. To help increase usability of wave data, the VWO will provide on its Web site tutorial materials on how wave

data might be used in heliophysics studies, and educational materials on basic wave physics to introduce students to the exciting science of wave phenomena.

2.5.5 Tools for Users and Data Providers

To promote utilization of heliophysics wave data, VWO aims to augment users' analysis capabilities by providing a set of uniform and robust tools to access and use distributed heliophysics-relevant wave data, metadata, and services. In addition, we plan to provide an assortment of basic data visualization and processing tools to aid in browsing and selecting data for further studies. Hyperlinks for accessing these tools and information will be collected and made available on the VWO website. For example, to assist data providers with data registration, members of the SPASE and VxO community are developing SPASE-related tools [30], including SPASE description editors, which data providers can use to produce SPASE-compliant metadata layers at their sites.

3. Science Examples Illustrating the Potential Use of VWO

A few examples of use cases may help illustrate how VWO can be put into practical use. For example, in studying how the Earth's auroral kilometric radiation (AKR, Figure 2) may depend on solar activity, solar wind, and geomagnetic conditions, a scientist may wish to compare AKR observations taken at different magnetic local times and latitudes under various conditions. This task can be facilitated by using VWO's context search capability based on the Magnetospheric-State Query System (MSQS) [31] to search for time intervals when a particular set of space environment conditions or magnetospheric state [9] occurs, including when solar activity is high (and low, for comparison). Additionally, the scientist can use VWO's location search capability, which is based on NASA's SSCWeb [32], to search for times when, for example, the Cluster, Geotail and Polar/IMAGE spacecraft were in specific locations to observe AKR in order to determine the variations of AKR emission patterns under different conditions. The user may also need to find times when polar and ground magnetometer stations are in magnetic conjunction in order to correlate space-based and ground-based observations. Each of these queries produces an event list at VQM (Figures 5 and 6), which can then determine the intersections between event lists to find the appropriate time intervals for further analysis. Using the resultant times from the VQM, VWO will then identify and retrieve the pertinent data granules from wave data sources such as CDAWeb and other VxOs, and return them to the scientist. Similarly, upstream solar wind data from Wind and ACE can also be obtained, so the user can identify possible interplanetary shock precursors of AKR events.

Another example of a possible application of the VWO can be illustrated by recent research on kilometric continuum (KC) radiation (e.g., [3]). This radiation is shown in Figure 7a as the nearly horizontal filaments that increase slowly in frequency with increasing UT. (The term "continuum" is a carryover from earlier research using receivers that lacked the frequency resolution to detect the fine frequency structure visible in Figure 7a.) The more intense (nearly vertical) emission features in Figure 7a with rapidly decreasing frequency with increasing UT are solar type III radio bursts. Kilometric radiation has been investigated for more than three decades, has been observed in every planetary magnetosphere visited by spacecraft with plasma-wave detectors, and has been the subject of several review articles [3, 33-35]. It has long been believed that KC is generated in regions of sharp density gradients, such as in the plasmapause, and that it occurs at all local times. Recent work [36] indicates that it originates in density bite-outs in the equatorial plasmasphere, called notches, as illustrated in Figure 7b. This conclusion was possible because IMAGE/EUV data defined the notch (see insert in Figure 7b) and allowed the plasmapause boundary to be displayed in equatorial distance as a function of magnetic local time, so as to be compared with the track of Geotail during the KC reception in Figure 7b. Ray-tracing calculations indicated that the KC was generated deep within the notch, and that the radiation beam was constrained by the notch structure in a manner consistent with the Geotail observations. To further understand the KC emission pattern and occurrences, a user may use the VWO to (1) locate KC observations by Geotail and Cluster, based on frequency range and spacecraft locations during times when notches appeared in IMAGE/EUV imaging observations; or (2) query other VxOs to locate possible notch observations during KC events; and/or (3) locate simultaneous multi-satellite KC observations of emissions from the same source region. Such capabilities will greatly facilitate the investigation of long-standing questions concerning all aspects of a wave research problem, i.e., wave generation, propagation, and reception, that is of fundamental importance to the wider heliophysics community as well as to the wave community. This is because information concerning the KC fine structure will also provide information on the dynamics and structure of the plasmapause source region.

The third example is inspired by a recent study by Muldrew [37]. As discussed by Benson and Fung [38], Muldrew [37] presented a theoretical model to explain the ionospheric-sounder-stimulated fundamental gyroharmonic emission that has defied satisfactory explanation for four decades. The confirmation of the model depended crucially on analyzing topside-sounder data obtained when the instrument was operating in an extended fixed-frequency sounding mode, and where the local gyro frequency (at the satellite location) matched the sounding frequency. The ISIS/Alouette data-restoration project [39] provided the pertinent topside-sounder data. Because the digital ISIS-2 sounder data include the metadata containing the

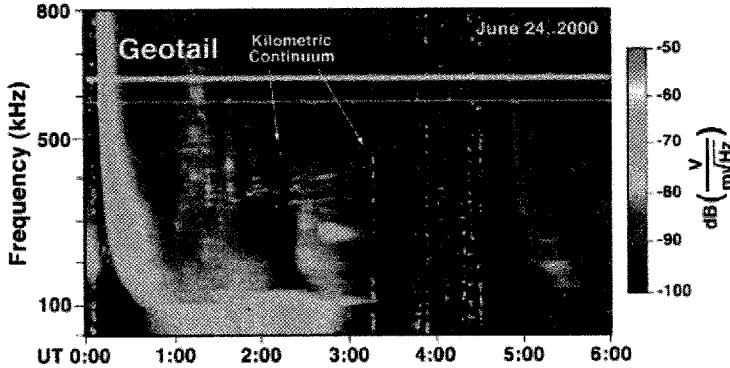


Figure 7a. The KC wave observations from Geotail/PWI (adapted from [2]).

local gyro frequencies at the satellite positions (based on a magnetic-field model), it was relatively straightforward to search [40] through more than 300,000 ISIS-2 digital topside ionograms to identify the data intervals satisfying the complex data-query conditions required by Muldrew's study. This example illustrates the benefit of the availability of *both* pertinent metadata and support for complex query for locating desired data granules for analysis. However, generally speaking, not all data sets will include specialized metadata. We expect that by using the SPASE data model for metadata descriptions, the query builder (Section 2.4) and the VQM (Figures 5 and 6), the VWO will be able to handle a variety of complex queries to effectively support heliophysics research.

4. Community Participation

The VWO is a discipline-oriented data service with the objective of supporting heliophysics wave research. Its development is guided by (i) the data needs of the wave-research community, (ii) the best practices adopted by the

heliophysics VxOs for interoperability (e.g., the use of SPASE and *SPASEQL*), and (iii) feedback from VWO users. To help make the VWO a successful research tool, active community involvement and input are therefore needed to:

- (1) Define community data needs,
- (2) Support the VxO framework and SPASE standards,
- (3) Make wave data sets available,
- (4) Annotate data, and
- (5) Provide user feedback.

5. Summary

We have introduced the Virtual Wave Observatory (VWO) as one of the VxOs forming the nascent heliophysics data environment. While most VxOs serve specific domains of interest (Section 1.2), the VWO caters to supporting

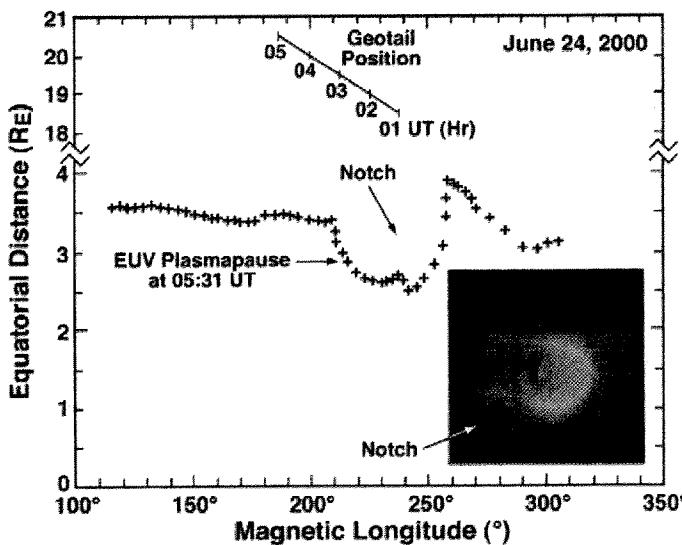


Figure 7b. The KC wave observations from Geotail/PWI (Figure 7a) map to a plasmaspheric notch structure as observed by IMAGE/EUV (adapted from [2]).

wave research using wave data obtained by sounding rockets, satellites, and ground stations in all heliophysics domains (e.g., Tables 1 and 2). Being a portal to such rich data contents, the VWO can benefit not only wave research, but also other heliophysics studies by enabling data comparisons, complex searches, and other services.

The VWO will provide unique data-search capabilities (Section 2.5.1) to support queries for heliophysics wave data. Such capabilities are ideal for conducting context searches for data obtained under the geophysical conditions (e.g., solar wind, magnetospheric state, etc.) and/or locations specified by the users [11]. With the support of SPASE-compliant metadata and *SPASEQL*, the same search capabilities can be applied to access data registered at other VxOs and distributed archives.

With the variety of heliophysics wave phenomena (electromagnetic, electrostatic, high and low frequency, trapped and freely-propagating, etc.), identifying a given set of observations with a particular phenomenon can sometimes be challenging to non-specialists. In order to increase the appreciation and use of wave data, the VWO will develop and post on its Web site [12] educational and tutorial materials to introduce the exciting science of waves, and to illustrate how wave data may be used in heliophysics studies. More importantly, VWO plans to develop an annotation service (Section 2.5.4) which will make searching for heliophysics wave data by phenomena possible, and more efficient and productive. Final success of VWO will depend on close collaboration between the VWO team and the wave researchers, whose input to the VWO (Section 4) will be highly valued.

Finally, it may be appropriate to give a few comments on the status of VWO development to date, and to provide an outlook of what is to come. Presently, about halfway into the three-year initial VWO development, the VWO team has helped develop the SPASE data model to enable basic descriptions of heliophysics wave data, although describing more-specialized wave data products may still require further data-model development. Using experience gained from applying SPASE to initially describe a few data sets (Table 1), we plan to develop a SPASE descriptor template for wave data. This template will be useful for constructing the VWO metadata database. A query builder with user interface, a part of the VQM (Figures 5 and 6), is being developed to support data search by context and location [11], as well as by time and platform. The VQM will be complemented by the development of SPASE-based search algorithms for locating, retrieving, and delivering data and information from data sources. As described in Section 2.5.4, VWO also plans to develop an annotation service patterned after the IMAGE RPI Expert Rating Service [12]. Although current VWO funding does not permit full annotation service development, we hope that in time it will become a key VWO feature that enables data search by phenomena.

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